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SYMMETRIZATION POSTULATE and PARASTATISTICS

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The quantum physics description of systems containing identical particles is very different from that in classical physics. One of the main differences is the dependence of the theoretical formulation of the type of particles being considered. The physical property of the particles which determines how they are treated quantitatively is their spin (a property, like angular momentum, that is expressed in units of integer or half-integer $\hbar$, where $\hbar$ is Planck's constant divided by 2π). According to quantum theory, the particles are divided into two types: those with half-integer spin called fermions, and those with interger spin called bosons. In terms of this nomenclature, for example, electrons (spin $\frac{1}{2}$) are fermions, and photons (spin 1) are bosons.

The assumed division of particles into these two types is called the symmetrization postulate. The symmetrization postulate requires that quantum mechanical states containing identical particles be either symmetric (bosons) or antisymmetric (fermions) with respect to an exchange of particles. Fermions, according to this postulate, have the property that only one fermion at a time may be in a given quantum state. This is in contrast to bosons, for which there is no such restriction.

The symmetrization postulate is generally regarded as necessary for constructing theories of identical particles in a consistent way and is introduced ad hoc into quantum theory. Numerous experimental successes in atomic physics, molecular physics, and quantum electrodynamics appear to provide firm support for the symmetrization postulate. The rotational spectra of homonuclear diatomic molecules and the success of the Pauli principle for electrons, which states that a system containing several electrons must have each electron in a different state, indicate that the electron and nucleons are fermions. Black-body radiation and the success of quantum electrondynamics suggest that photons are bosons. In view of these well-established results, the symmetrization postulate is usually assumed to apply to all other particles.

Recently, however, O. W. Greenberg (1) of the University of Maryland, with the support of the Nuclear Physics Division of AFOSR, completed an exhaustive study of the theoretical justification and the experimental evi-

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dences for the symmetrization postulate. His collaborator in the study was A.M.L. Messiah of the Center of Nuclear Studies at Saclay, France. Messiah and Greenberg investigated the foundations of the postulate from two viewpoints: particle quantum mechanics and quantum field theory. These two approaches are known to be equivalent in the cases of fermions and bosons; whether this would hold true for the possibility of particles not classifiable as fermions or bosons remains an open question.

Messiah and Greenberg show that particles which do not obey the symmetrization postulate can be accommodated in quantum theory without violating any of the basic principles. The major change in the structure of the theory is that the wave function, which gives the mathematical description of a quantum state, must be generalized. One of the interesting conclusions of this "generalized" quantum theory is that the indistinguishability of the particles being considered does not imply the need for the symmetrization postulate; rather, it restricts the interactions which they will undergo.

Based on this more general quantum mechanical viewpoint, experimental results of all particle collisions presently available in high-energy particle accelerators indicate that the symmetrization postulate is valid. These experiments are somewhat limited, since the colliding particles are always either fermions or bosons. For other cases, convincing tests of the symmetrization postulate are very hard to obtain, mainly due to the lack of detectable interference between interactions that obey and interactions that violate the postulate. For example, the symmetrization postulate is well established for electrons, nucleons, and photons; strong evidence is accumulating that pions (pi mesons) are bosons. Messiah and Greenberg discuss

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JACOB SEIDEN
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a method whereby it may be possible to test the lambda particle. It does not appear possible to establish whether particles such as the muon, kaons, and sigma minus obey or violate the symmetrization postulate.

Since evidence compiled from the viewpoint of quantum mechanics gives no a priori reason against the existence of particles other than bosons or fermions, it is natural to carry this general viewpoint over to field theory. Specifically, quantum field theory need not be formulated in accordance with Fermi or Bose statistics, wherein fermions and bosons are the only types of particles, but may be formulated in a broader sense in accordance with what is called parastatistics. The first attempt at a more general quantum field theory, known as parafield theory, was carried out by H. S. Green (2) in 1953. In Green's formulation, quantum field theory based on ordinary quantum statistics is a special case.

Parastatistics differs from ordinary quantum statistics in several ways. Parafermions (half-integer spin particles) divide into groups of particles and may be distinguished only as members of different groups. As in ordinary Fermi statistics, which deals with only one group of particles, not more than one particle in a group may exist in a given state. Parabosons differ from parafermions only in that any number of particles can be in the same group and the same state. In both cases, the number of groups determines the order (k) of the statistics. For order k=1, parafermions reduce to fermions and parabosons to bosons.

Messiah and Greenberg (3) extended the investigations of Green by determining the rules that para and ordinary particles must satisfy when interacting. The rules are as follows: (1) the total number of fermions and parafermions (counting both particles and antiparticles as positive) on both sides of a reaction must be even; (2) for para particles of each even order k, the total number of para particles of order k on both sides of a reaction must be even; (3) for para particles of each odd order k, the total number of para particles of order k on both sides of a reaction can take any value except for odd numbers smaller than k. Combining rules (2) and (3), one can see that for each order k at least two para particles must enter into every reaction. Due to this stringent requirement, presently available experimental evidence implies that no presently known particles are para particles.

Though experimental evidence seems to indicate that no presently known particles are para particles, this does not eliminate the possibility of their existence. Recently, Greenberg (4) has shown that the group theoretical classification of particles, SU(6)--a larger classification scheme than the "eightfold way" of Gell-Mann and Ne'eman which was used to predict the omega-minus particle--requires the possible existence of parafermions of order three. The particles which must be parafermions are the "quarks" or basic building-block particles of the SU(6) model. (5)

The quarks arise in this model through the assumptions that baryons and mesons are composite, that they are composed of basic particles, and that the basic forces between the particles are approximately independent of certain quantities, such as spin, which characterize the particles. The particles are classified in multiplets according to their masses. The two lowest groupings for the baryons and mesons contain 56 baryons and 35 mesons. The mesons are constructed from a quark and an antiquark, which are distinguishable. Both ordinary and parafield theory will thus lead to the same results for mesons. (6) However, this is not the case for baryons which are composed of three identical quarks. The experimentally verifiable results of this model agree best with experiment if the quarks used to construct the baryons are parafermions of order three.

In summary, there is no conclusive evidence against the existence of particles other than bosons and fermions in nature. If they exist, these other particles must satisfy certain very restrictive rules in particle quantum mechanics and quantum field theory. From a quantum mechanical viewpoint, no experiment now possible would produce the non-Bose or non-Fermi particles. Experimental

results compiled in verification of the more general field quantization show that no particles now known are para particles. However, this does not eliminate the possibility that para particles do exist. ★

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explosive warming in the stratosphere

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In January 1952, a German meteorologist observed that the temperature of the stratosphere over Berlin rose 30 degrees C in less than 2 weeks. Comparable changes in temperature in the atmosphere's bottom layer, the troposphere, are common; but this was the first time such a rapid, or "explosive" warming had been observed in the stratosphere. Meteorologists were puzzled because this region of the atmosphere, extending roughly from 10 to 60 km., was thought to be extremely stable, with wind and temperature patterns persisting for months with little change. Since that time, a number of explosive warmings in the stratosphere have been observed, and the meteorologist is confronted with the problem of explaining them.

One obstacle to such an explanation is the inadequacy of present models of the stratosphere's thermodynamic characteristics. An AFCRL meteorologist, Dr. H. Stuart Muench, has developed a mathematical model, however, that describes the stratosphere's energy processes in enough detail to make possible a satisfactory theoretical treatment of stratospheric warming.

The energy processes of the stratosphere, like those of the atmosphere as a whole, mainly involve the conversion of heat into mechanical energy in the form of wind. The reverse also occurs when friction between adjoining layers of air, or between air and the earth's surface, dissipates mechanical energy as heat. In simplified form, the model which Muench derived is a flow chart showing the directions in which conversion of one form of energy to another takes place. In this way, the correctness of the model can be checked by determining how well the observed inputs and outputs of energy balance. The model is similar to the classical model of the entire atmosphere as a "heat engine" that uses solar energy to drive atmospheric circulations. The main difference between Muench's model and others is that his model takes into account certain "boundary conditions" that indicate the transfer of energy between the stratosphere and the troposphere below it. Such boundary conditions involve vertical air currents which transfer heat, momentum and gravitational potential energy. With the help of this model, Muench concluded that explosive warming of the stratosphere is caused by a disturbance propagating upward from the troposphere across a somewhat ill-defined stratosphere-troposphere boundary.

This conclusion appears to be so reasonable that one might wonder why there was a problem in the first place. To understand the difficulty meteorologists have had explaining explosive warming, let's look at the differences between the physical processes in the troposphere, familiar as weather, and those in the stratosphere. Perhaps the primary difference between the two layers lies in their stability. The troposphere, acting like a heat engine, tends to make disturbances originating in it grow. The stratosphere, on the other hand, acts like a brake, to damp out disturbances. This damping action results from the fact that, in the lower stratosphere, temperature remains fairly constant over a wide range of altitudes, then gradually increases with altitude in the upper strato-

sphere. This thermal structure tends to prevent the turbulent rising of warm air and falling of cold air which is the primary way thermal energy is converted into the mechanical energy of relatively small-scale, transient disturbances such as tropospheric storms. (In the troposphere, temperature decreases rapidly with altitude.) Thus, any sudden change in the stratosphere's "weather"--a rapid rise in temperature, for instance--must, in some way, have overcome the damping effect of the stratosphere. Muench believes that only a disturbance propagating upward from the troposphere could overcome the stratosphere's resistance to change.

Associated with such explosive warmings, which have been observed to occur on the average of about once every three years, is the disruption of the circumpolar westerly winds which constitute the stratosphere's predominant wintertime circulation pattern. During an explosive warming, the temperature in large regions of the stratosphere generally increases from around -60 degrees C to -30 degrees C in less than a week. The warmings have occurred most often in mid-January, and so far have been observed only at northern latitudes. Since the first observed warming in 1952, their occurrence has been rather sporadic--in 1957, 1958, 1963 and 1965 (the last one observed in March 1965 over the U.S.). Otherwise, the only changes in the stratosphere are the slow, large-scale seasonal shifts in temperature and circulation that repeat themselves year after year. ★

LECTURE SERIES IN DIFFERENTIAL EQUATIONS

DR. R.G. POHRER

Directorate of Mathematical Sciences, AFOSR

The Mathematics Division, AFOSR, in conjunction with the Graduate Consortium of America--Catholic, Georgetown, George Washington and Howard Universities of the District of Columbia, and the University of Maryland--is sponsoring a Lecture Series in Differential Equations in the greater Washington area during the academic years 1965-66 and 1966-67. Eight sessions of three lectures each are scheduled. They are to emphasize particular problem areas of Air Force interest and application.

To date, two sessions have been held in the areas of control theory and dynamical systems. The lecturers in each area have been G. B. Dantzig, S. Lefschetz and L. Markus, and W. Gottschalle, S. Kakutani and L. Auslander, respectively. Interested individuals and organizations can receive announcements of future sessions upon request. In addition, the papers delivered at each session will be available as AFOSR scientific reports in limited quantities at the conclusion of the series.

The first report on control theory, summarizing the presentations of Professors Dantzig, Lefschetz and Markus, has already appeared. Professor Dantzig's paper illustrates how mathematical programming, in particular a generalized linear program, can be applied to a linear control process. The "problem" takes the form of minimizing the "cost" of moving an "object" from one convex domain to another by proper choice of a control vector and boundary conditions.

Professor Lefschetz's paper deals with the Lurie problem on nonlinear controls, i.e., the determination of necessary and sufficient conditions such that all solutions of a set of general nonlinear control differential equations are absolutely stable. This means that all solutions are asymptotically stable in the large whatever the choice of the admissible (function) characteristic of the control.

Professor Markus discussed the "bang-bang" theory of control as a physical concept and as a collection of precise mathematical theorems. The bang-bang principle, of course, states that any response of a controlled system which can be achieved by an arbitrary controller varying over the total control domain can be equally well achieved by a controller restricted to the extreme values of the control domains. Theorems presented relate both to linear and nonlinear control processes.

Copies of this report are available and have been distributed to each participant in the session. A limited number of additional copies are available upon request to the Mathematics Division, AFOSR.

The Contribution of Hydrogen-Dislocation Interactions to the Embrittlement of Iron & Steel

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The catastrophic failure of high-strength steel parts in service has been of particular concern to the aircraft and aerospace industry for many years. Most of the failures encountered could be attributed to hydrogen embrittlement--either as slow-strain-rate embrittlement (dynamic loading), or as delayed failure (static loading). Most scientists and engineers have tended to classify both types of embrittlement under the simple heading of hydrogen embrittlement, and the results of research investigations into the mechanism of one type have generally been extended to the other.

Many different workers have investigated slow-strain-rate embrittlement. Most of them conclude that hydrogen atoms escape from solution and combine to form hydrogen gas at areas where voids or low-energy interfaces (such as an inclusion) exist. The gas exerts sufficient pressure within these cavities to cause premature crack propagation when relatively low levels of external stress are applied.

Most of the research on the delayed-failure mechanism has been conducted by Professor A. R. Troiano and his many students. In their research on a number of other materials with a variety of solutes in addition to hydrogen, they found a quite reasonable correlation between strain aging and delayed-failure behavior, leading them to conclude that hydrogen is damaging through a lattice effect. Since strain aging is exemplified by interactions between solute atoms (generally interstitials) and dislocations, and since rather conclusive evidence exists for a yield point in iron and steel due to hydrogen, one further contribution to embrittlement could be hydrogen-dislocation interactions which favor crack propagation.

The above consideration was the basis for a recently completed study at ARL. Hydrogen-dislocation interactions were investigated in a zone-refined iron by means of the Petch relationship, $\sigma LY = \sigma_o + k_y\, d^{-1/2}$, where the lower yield stress (σLY) is plotted versus the inverse square root of the grain diameter ($d^{-1/2}$). For a range of grain sizes, the resultant plot yields two significant parameters: σ_o, which is a measure of the resistance of the lattice to moving dislocations; and k_y, which is a measure of the relative ease of initiating macroscopic plastic deformation. Specimens having five different grain sizes were compared in each of three conditions: (1) cathodically charged with hydrogen, (2) uncharged, and (3) cathodically charged with hydrogen and evacuated to remove the hydrogen. The resulting Petch plot is shown in Figure 1. Upon hydrogen charging, there is a substantial reduction in the slope (k_y) and a substantial increase in the intercept (σ_o). The reduction in K_y and the increase in σ_o essentially remain when the hydrogen is removed. The ductility, however, is very dependent on the presence of hydrogen. Figure 2 shows the per cent elongation plotted versus $d^{-1/2}$ (for convenience only). A significant improvement in ductility results upon hydrogen removal, and complete recovery of ductility is experienced by the two finest grain sizes.

Since the parameters which reflect hydrogen-dislocation interactions (σ_o, ky) are much more dependent on the fact that hydrogen was introduced cathodically than on the presence of hydrogen, and since the opposite is true for the ductility, any contribution to embrittlement by hydrogen-dislocation interactions is a very minor effect. These results tend to support the gas-pressure theory for slow-strain-rate embrittlement and, in view of the excellent correlation between the delayed-failure behavior of the variety of materials studied and a mechanism based on lattice effects, these results further suggest that the delayed-failure process and the slow-strain-rate embrittlement process are different in kind rather than degree. This seems reasonable since slow-strain-rate embrittlement results after relatively large amounts of plastic strain, whereas delayed failure generally does not. ★

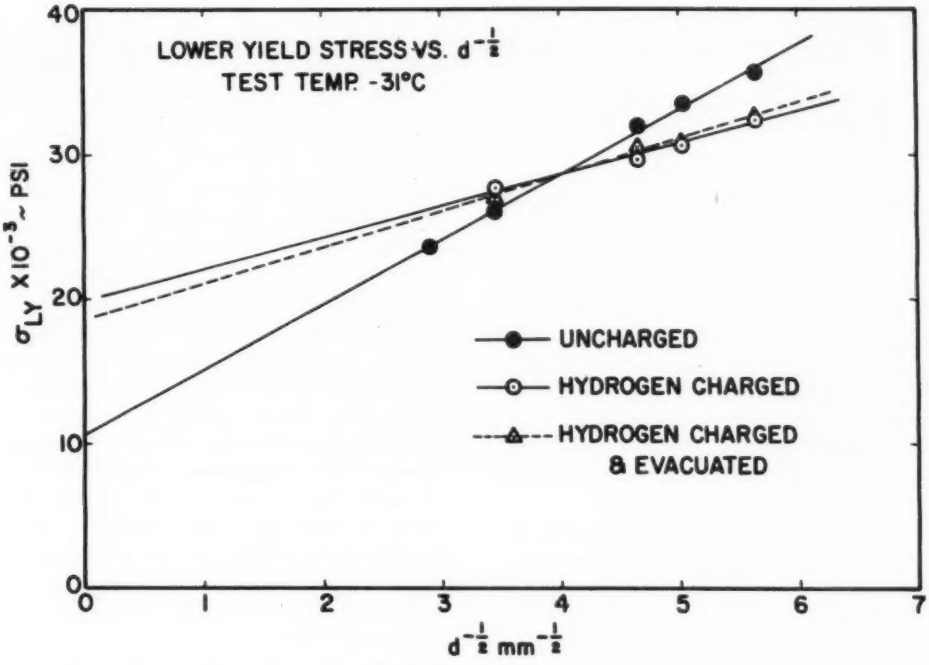

Figure 1.

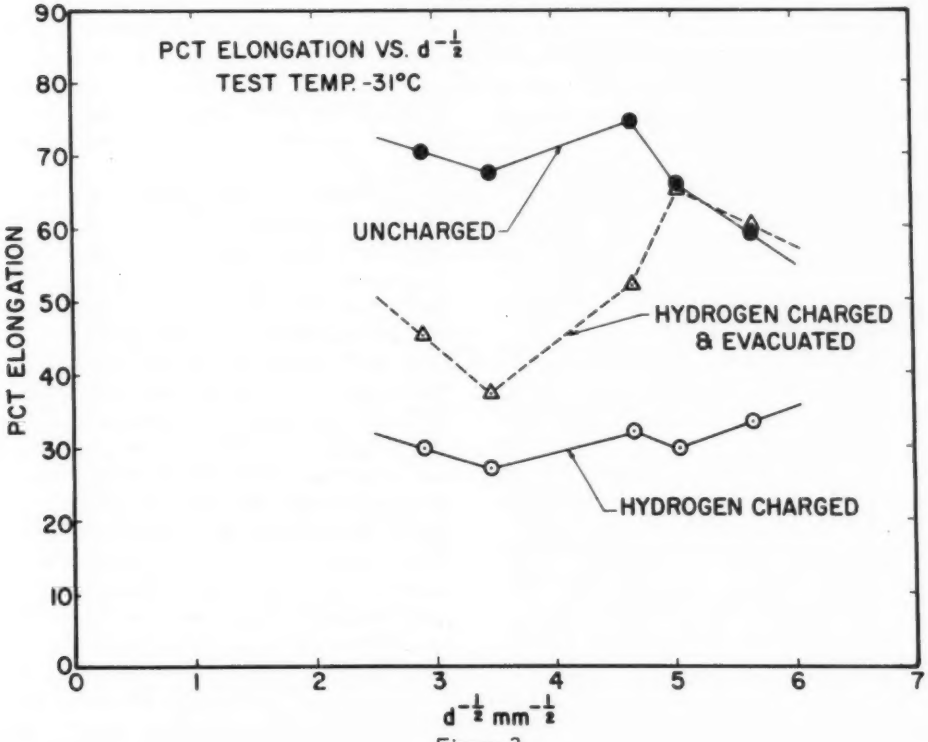

Figure 2.

heat-transfer measurements utilizing instrumented honeycomb panels

CAPTAIN KARLHEINZ O.W. BALL
Hypersonic Research Laboratory, ARL

The study of flow separation at hypersonic speeds represents a major research effort of ARL's Hypersonic Research Laboratory. A segment of this program is directed at measuring the aerodynamic heating rates to a compression corner model at a Mach number of 12 and stagnation temperature up to 1900°R. Stainless-steel honeycomb-sandwich panels are to be utilized for the instrumented sections of the model.

This note describes the work done to determine the response to heat flux of a honeycomb-sandwich panel and an unsupported face sheet. Heating rates up to 5 BTU/ft^2-sec were encountered at a time of 1.5 seconds after exposure to temperature up to 2100°R. The results are presented in terms of heating rate correlation between the honeycomb-sandwich panel and the unsupported thin sheet.

Several experimental techniques have been developed for obtaining heat-transfer rates in wind-tunnel testing. The "thin-skin" or transient temperature method is commonly used. The method is obtained by equating the heat transferred to the skin, $h(T_{aw}-T)$, with the heat stored per unit area, $\rho cd(\partial T/\partial t)$, in the skin of thickness d. In the above, h is the heat-transfer coefficient, T_{aw} the adiabatic wall temperature, T the surface temperature, ρ the skin density, c its specific heat, and t is time. The more important assumption inherent in the "thin-skin" method is that the heat conduction is across the skin and none is along the skin, i.e., the temperature is assumed to be uniform across the skin thickness. In addition, the material properties are usually assumed constant. Experimentally, the method requires that the model be constructed with as thin a skin as possible to obtain a fast response, but yet thick enough to maintain structural integrity. Honeycomb-sandwich panels appear to meet both requirements, depending of course on the panel geometry.

Four test panels, each 3 X 3 X 1/4 inches, were manufactured from type 321 stainless steel. Two of the panels had cover sheets of 0.010-inch thickness, while the other two had sheets of 0.019-inch thickness as the panel outside cover and 0.010-inch thickness as the panel inside cover. In each of these two sets of panels, one of the panels was of honeycomb-sandwich construction with a cell cross section having a dimension of 0.25 inch and a web thickness of 0.0015 inch. The second panel of each set did not have the honeycomb, but the front and rear sheets were separated by 0.25-inch spacers at each corner. The honeycomb material was also of 321 stainless steel. A sluggishly flowing silver alloy with a low thermal conductivity was used as the brazing alloy for the honeycomb to cover sheet joints. Each honeycomb cell wall contained small holes to provide pressure relief during the manufacturing process and during testing.

In order to spot weld two thermocouples (chromel/alumel) to the rear face of the outside cover sheet, each test panel had two sections removed from the back sheet. The opened section in the honeycomb panel consisted of a 4-cell cutout.

The heat flux was obtained from an oven having a maximum temperature capability of 2500°R. A test consisted of raising the oven to a specific temperature, rapidly inserting a test panel into the oven manually, about 0.2 second, and recording the temperature of the oven as well as the temperature of the test panel as a function of time on a strip chart recorder operating at a rate of about 5 inches per second. The temperature of the test panel was recorded on a 75°F to 200°F type scale (6 inches), and the oven temperature on an 800°F to 1700°F type scale (6 inches).

For data reduction, the starting time was taken at the point where heating of the test panel actually began after insertion into the oven. This point was clearly defined on the test panel temperature versus time traces. The slope of the traces 1.5 seconds after the start of heating defined dT/dt. Heating rates were then obtained through the use of

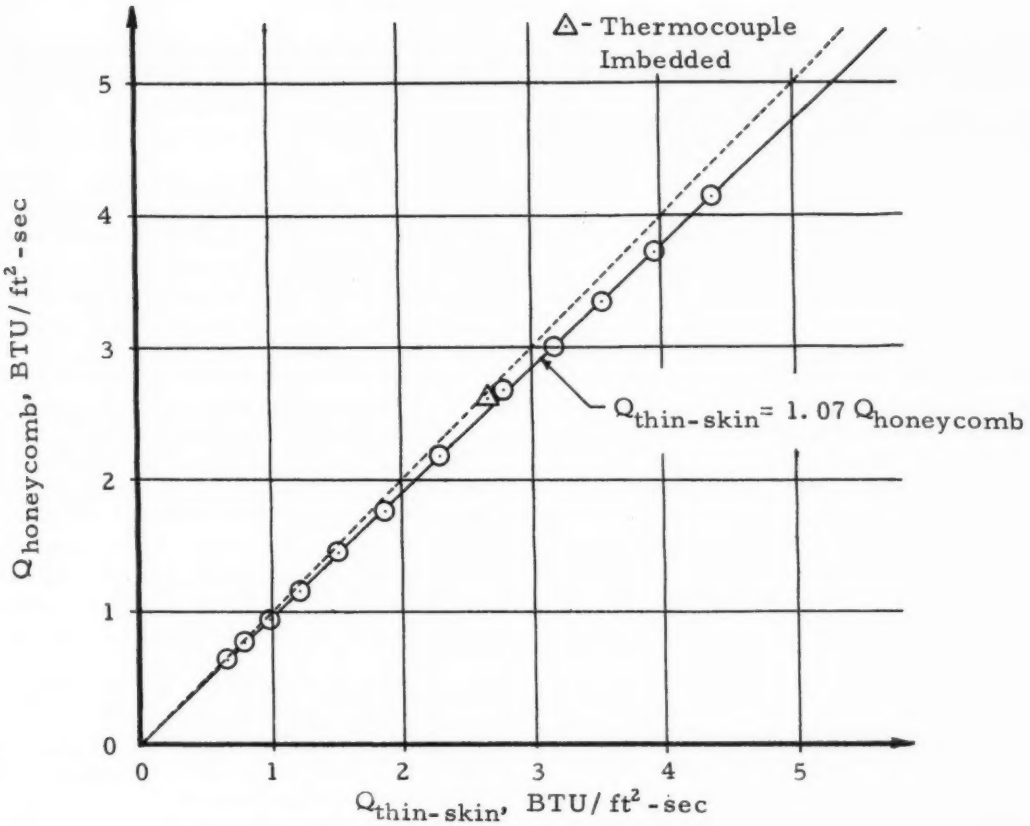

Fig. 1. Correlation of Heat Transfer.

the transient one-dimensional heating rate $\rho cd(dT/dt)$. For 321 stainless steel the density used was 501 lb/ft^3, and 0.12 BTU/lb^{o}F was used as the specific heat.

The program was initiated with testing of the set of test panels having 0.010-inch thickness for the outside cover sheet. The honeycomb panel of this set began to take on permanent waviness on the outside cover sheet after about 10 exposures to temperatures up to 2000^{o}R. Further testing of this set was discontinued and no data is presented.

The data from the tests of the set of panels having 0.019-inch thickness for the outside cover sheet was reduced to heating rates. Figure 1 presents the correlation of measured honeycomb-panel heating rates against the heating rates measured on the unsupported, "thin-skin" panel. This data represents temperature rates measured 1.5 seconds after insertion of the test panel; however, the data showed that had 2.5 seconds been chosen for data reduction, the temperature rates would have been identical. It should also be pointed out that both thermocouples on a given test panel gave identical results.

With reference to Figure 1, it is seen that the honeycomb panel lags the "thin-skin" panel by a constant 7%. This is attributed primarily to conduction loss to the honeycomb webs. Imbedding the thermocouple in a silver solder just under the skin reduced this lag; but the distortion to the surface caused by the high-temperature soldering process and subsequent machining eliminated this method of thermocouple installation.

It is concluded that, for the specific honeycomb configuration tested, other experiments using the same configuration may be corrected to obtain the equivalent, supported "thin-skin" heating rates by multiplication of a factor equal to 1.07. ★

IMPERFECT BY ONLY FIVE PARTS IN TEN MILLION! (or long live crystal defects)

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The above title, at first glance, will probably cause the semiconductor specialist to assume a smug mien and blasé attitude toward the newsworthiness of this article. For after all, has not germanium been freed of various chemical impurities to the extent perhaps of five parts in ten billion or better since the advent of zone melting?. What, therefore, is exciting about parts per ten million? Let us hasten to add, however, that the state of purity is far from the whole story. There are, in fact, large classes of semiconductors where, at the present stage of technology, the electrical performance is limited not by the concentration of impurity atoms, but rather by the density of physical imperfections or defects.* These materials are mostly compounds and are highly useful as infrared detectors and emitters, nonlinear junction-type devices operating at low temperatures, potential microwave detectors and Gunn-type oscillators, as well as certain kinds of lasers.

By the term physical imperfections, one commonly refers to such atomic defects as point defects, dislocations, stacking faults, etc. They are deviations from the regular structure and charge distribution which are characteristic of the crystal structure of the solid. Actually, it is the presence of specific chemical and physical imperfections which renders many materials of value in a wide variety of applications. A slab of absolutely perfect germanium or silicon would be useless as a transistor or rectifier. Certain metals, if completely defect-free, might lose most of their ductility. Thus, we see that even minor concentrations of defects can alter profoundly the properties of the host material. The problem is to determine what imperfections are initially present in a crystal, and their respective concentrations, to understand the effects of these imperfections, and their interactions, and to place limits on the allowable concentrations for a specific use of the material. In other words, one must characterize the material for a given application. The procedure, then, is to insure that the density of undesirable defects be below the tolerance level and, when necessary, to introduce the appropriate concentration of desirable imperfections in the correct place in the crystal.

In this article, we shall be concerned principally with point defects. These may be vacancies, interstitials, or antistructure defects. In the latter case, atoms of one element occupy lattice sites of another. It is well known, of course, that at any temperature above absolute zero there exists a certain equilibrium concentration of lattice defects. Each of these defects often contributes one or more charge carriers, and the practical problem comes into existence when the defect density is so large as to prevent utilization of the desirable intrinsic properties of the material in question. Even though the device is used at room temperatures or below, the situation is rendered more severe by the presence of "frozen-in" defects resulting from preparation of the crystal at higher temperatures. As a result, many useful compound semiconductors, as normally prepared, possess donor or acceptor concentrations several orders of magnitude higher than is desired for many applications. Furthermore, as is obvious from the above, no additional purification of constituent elements or compounds can reduce this "residual" carrier concentration.

Under sponsorship of AFOSR, inroads into this problem are being made by Dr. A. C. Beer and a group of solid-state physicists and chemists at the Battelle Memorial Institute laboratories at Columbus, Ohio. The material which has been the subject of investigation is gallium antimonide (GaSb). This compound is easily prepared--having a melting temperature of only 706°C, and an absence of excessive vapor pressure at the melting point. Yet it is representative of a large number of semiconducting compounds, inasmuch as the maximum melting temperature of the compound does not occur precisely at the 50-50 stoichiometric composition. Consequently, standard preparative techniques always yield material with a residual acceptor content responsible for

1 to 2 x 10^{17} positive charge carriers (holes)/cm^3 at room temperature, regardless of the degree of purification of the elements or the final compound. (1-5)

In establishing the probable nature of the residual acceptor centers, use was made of information obtained by chemical, electrical, and metallurgical methods. For example, analysis of highly pure material by the mass spectrograph has shown essentially no chemical impurities to be present in sufficiently high concentrations to account for the observed residual acceptor density, with the possible exception of silicon, hydrogen, nitrogen, oxygen, and carbon. (6) Many of these impurities are improbable as a result of studies involving variation in preparation procedures. Other inpurities are highly unlikely candidates as residual acceptor centers because of their known behavior in GaSb and other III-V compounds. The diffusion of lithium is a powerful tool for learning more about the nature of the residual centers. From initial studies of activation energies of the acceptor levels through electrical measurements done as a function of temperature, it was found that the center in question was associated with a relatively deep level (about 0.035 ev above the valence band) and also was capable of a second ionization--thus precluding the existence of merely a simple hydrogenic-type level. Small additions of lithium, by diffusion, produced a pairing with the ionized centers, thereby extinguishing the deep-lying level and producing a purely hydrogenic kind of level (about 0.01 ev above the valence band). (7-9) This resulted in a substantial increase in mobility of charge carriers as well as a decrease in their density. The latter result confirms again the thesis that the effect of the lithium treatment is not a compensation of acceptors by donors, but rather is a pairing reaction. (10) A further confirmation of the pairing reaction was obtained from studies of the lithium solubility as a function of temperature, and associating this information with the known density of the residual acceptor centers.

The ionization characteristics of the acceptor sites were also confirmed by studies of the behavior of the levels as the p-type material was compensated with tellurium (donors), eventually yielding n-type material. Subsequent treatment of the n-type GaSb with lithium indicated that the basic interaction between lithium and the residual acceptors was not changed when donors predominated. In fact, a comparison of the electrical properties of n-type samples before and after the addition of lithium led to a model for the residual centers, which coincided with that for p-type samples.

The composition of a compound which normally tends to be off from stoichiometry because of the maximum melting temperature not occurring at the stoichiometric composition may often be adjusted by growth from a melt which contains an excess of the appropriate constituent--in this case, antimony. This is possible as the maximum melting point is on the gallium-rich side of the 50-50 composition. In the case of GaSb, however, the initial application of such techniques did not produce noticeable results--presumably because of the nature of the phase diagram of the gallium-antimony system. In particular, the slope of the liquidus deviates only slowly from horizontal as the melt composition is changed from that composition which is characteristic of the highest melting point of the compound. With extreme differences in melt composition, however, Effer and Etter found that significant results could be achieved. (5) Difficulties exist in regard to obtaining single crystals of good uniformity from such melts; but these problems are soluble, and the Battelle group was able to use melts with antimony/gallium ratios of nearly 3/1. These techniques reduced the residual acceptor concentration by an order of magnitude and increased mobilities of the holes in the GaSb at 350°C by as much as a factor of two. Another important observation is that the residual centers are characterized by an over-all antimony deficiency, or gallium excess. A simple gallium interstitial, however, would be expected to be a donor. Also, it is unlikely that a simple antimony vacancy could act as an acceptor, especially one capable of a double ionization. Therefore, the most likely arrangement appears to be a type of antistructure defect in which

a gallium atom resides on an antimony site. Of course, an accompanying rearrangement of the lattice could be associated with the simple antistructure.

As a result of the investigations described above, it was possible to establish fine structure in the phase diagram. In Fig. 1a we see the phase diagram for the gallium-antimony system as established by Greenfield and Smith. (11) The stable composition range for the zinc blende phase is so narrow on this scale that the solidus is represented by a straight line. From a quantitative determination of residual acceptor densities by analysis of the electrical properties of a series of samples, and by use of the model discussed above for the defect nature of the acceptor centers, it was possible to establish in minute detail the behavior of the solidus near its maximum. This is shown in Fig. 1b. Note that the units on the abscissa scale represent one part in a million!

In conclusion, it is to be noted that the characterization of a solid with respect to the density and nature of its physical imperfections, or defects*, is in general more difficult than the determination of chemical impurities. Nevertheless, the specification of a material merely in terms of its impurity content is in many cases woefully inadequate, not only for the so-called "communication" materials--i.e., those which participate actively in electronic devices--but also for structural materials employed in many critical mechanical and thermal applications. Many serious difficulties can arise from the behavior of point defects, dislocations, etc., under severe operating environments. For example, the strength of metals and their response to heat treatment are strongly influenced by the action of defects. Well-known examples of the effects of defects in communication materials are degradation of minority-carrier lifetime, undesirable diffusion of foreign atoms under temperature gradients, etc., while examples in the case of the structural class of materials include phenomena such as kinetics of recrystallization, fatigue, brittle fracture, etc. For these reasons, adequate characterization and understanding of the properties of defects is highly important, both in materials for electronic applications and for structural applications--especially where the environment may be unfavorable from the standpoint of temperature, stress, corrosive chemicals, or radiation effects. The techniques available for investigating defects are becoming more varied and more extensive. The case of GaSb was an example of how both the concentration and the nature of residual acceptor centers could be elucidated. Continued application of such approaches to other materials will most likely be forthcoming upon application of sufficient research effort. In fact, it is the complex area of defect control which offers the exciting challenge for future solid-state research, and which holds promise for the development of new and improved properties in materials. The impetus for such activity is on a continual increase as modern technology places more and more stringent demands on materials, especially as regards reliability and the ability to perform under increasingly severe environments. ★

For a more detailed discussion of the nature and importance of imperfections in solids, the reader is referred to References 12-16.

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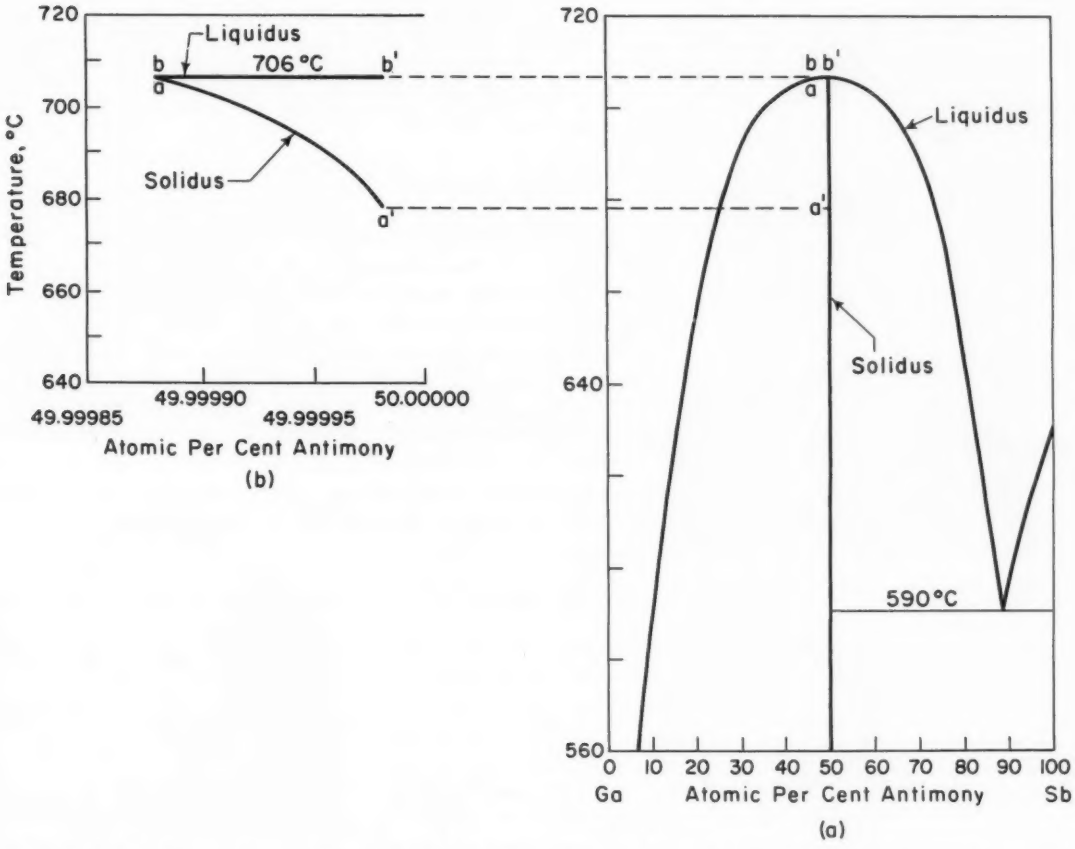

Fig. 1. (a) Ordinary phase diagram for the Ga-Sb system. (b) Greatly expanded abscissa scale revealing fine structure in the solidus aa'. Due to the narrowness in over-all composition now covered by the expanded abscissa, the deviations in the liquidus from horizontal are too small to be seen. The data sensitive enough to delineate the fine structure were obtained by analysis of electrical measurements.

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PROFILES

Dr. Thomas W. Myers is a visiting research associate at the Thermomechanics Research Laboratory, ARL. He received the B.S., M.S., and Ph.D. degrees in Mechanical Engineering from the University of Missouri, Columbia, Missouri, in 1961, 1963, and 1965, respectively. During his graduate studies, Dr. Myers held a National Defense Education Act Fellowship and was an assistant instructor. His dissertation research was concerned with a magnetically balanced electric arc in a transverse gas flow. He is continuing this research at ARL on the energy-transfer and aerodynamic aspects of electric arcs in transverse gas flows and magnetic fields. In this Review, Dr. Myers writes "On Investigations of Stationary Magnetically Balanced Electric Arcs in Transverse Gas Flows."

Dr. Keith A. Browning is a research physicist with the Weather Radar Branch, Meteorology Laboratory, Air Force Cambridge Research Laboratories. He attended the Imperial College of Science and Technology (London University) where, in 1959, he received his B.Sc. (Special) and A.R.C.S. in Physics, and subsequently, in 1962, his Ph.D. and D.I.C. in Meteorology. Currently, Dr. Browning is principally concerned with the use of radar to investigate the interrelation of air motions and precipitation development. He is a Fellow of the Royal Meteorological Society, and a Professional Member of the American Meteorological Society. In the March 1966 issue of the Review, Dr. Browning's work as editor of an AFCRL comprehensive report on a family of storms is described in the article, "Anatomy of a Severe Storm."

Captain Karlheinz O. W. Ball at the Hypersonic Research Laboratory, ARL, is currently conducting research on hypersonic boundary-layer separation with heat and mass transfer. He received his B.S. (Aeronautical Engineering) from the University of Alabama in 1957, his M.S. (Aerodynamics) from the Georgia Institute of Technology in 1958, and a Certificate (Exper. Aero.) from the von Karman Institute for Fluid Dynamics in 1959. Captain Ball is presently a candidate for a Ph. D. in Aeronautical Engineering at the University of Southern California. His experience includes 18 months as an aerodynamicist with the Army Ballistic Missile Agency, Huntsville, Alabama, and 3 years as a project officer, 3rd Stage Minuteman, AFBSD, Los Angeles, California. In this issue of the Review, Captain Ball discusses "Heat-Transfer Measurements Utilizing Instrumented Honeycomb Panels."

Dr. Wolfgang G. Braun, Plasma Physics Research Laboratory, ARL, is engaged in spectrographic studies of high-energy transient electrical discharges through ionized gases. He is currently studying the flow stabilization of electrical discharges. His previous work has included an experimental and theoretical investigation of the transients that appear in the sudden discharge of a circular disc condenser. Dr. Braun received the M.E. degree from the Technical University of Vienna in 1937, and the Dr.-Ing. degree from the Technical University of Darmstadt in 1957. He has been associated with the U.S. Air Force since 1948, working in electronics and plasma physics, and has a number of publications to his credit. His article, "Kirchhoff's Law and the Radiant Plasma," is in this issue of the Review.

Mr. Attwell M. Adair, a physical metallurgist with the Metallurgy and Ceramics Research Laboratory, ARL, is investigating, with Mr. R. E. Hook, the effect of interstitial hydrogen on the yield and fracture stress of zone-refined iron to determine the existence and nature of hydrogen-dislocation interactions and the relationship of such effects to the hydrogen-induced delay-failure phenomenon. To gain insight into the significance of the interactions between line and point defects in metals, Mr. Adair is studying the kinetics of the low-temperature yield points in metals over a suitable temperature range. Mr. Adair received his B.S. in Metallurgical Engineering from the University of Kentucky in 1952, and his M.S. in Metallurgy from Ohio State University in 1954. With ARL since 1954, he is the author of a number of publications in his specialty. His article, "The Contribution of Hydrogen-Dislocation Interactions to the Embrittlement of Iron and Steel," appears in this issue of the Review.

Kirchhoff's Law & the Radiant Plasma

DR. WOLFGANG G. BRAUN, Plasma Physics Research Laboratory, ARL

Spectrophotometric measurements represent a powerful diagnostic tool for the determination of various parameters in a plasma as well as for the experimental determination of atomic properties. In general, an experimental plasma is not homogeneous and local values of the radiometric quantities must be found before such parameters as particle densities and temperatures can be derived from the measurements. In the case of a plasma which is not optically thin, additional information may be obtained from absorption measurements. The radiant-energy flux coming from a volume source is related to the local coefficients of emission, j, and absorption, a, by an integral equation. The determination of the spatial distribution of the coefficients from a number of co-ordinated observations across the inhomogeneous plasma (brightness profile) amounts to solving this integral equation. A solution is possible if the properties of the plasma display circular cylindrical symmetry, as is the case with the column of an electrical-arc discharge. However, if self-absorption in the plasma is present, the spatial distribution of the absorption coefficient, a (r), in the plasma column must be found first.

A variation of the Double Path Method for the measurement of the absorption coefficient in a plasma has been developed at ARL which is much less sensitive to a misalignment of source and image than the original method, and yields transmission factor measurements of uniform accuracy across the entire source. The major component of the system is a stigmatic spectrograph with photoelectric read-out. It is needed for the resolution in wave length. The source investigated is the column of an electric arc of extreme brightness; it is imaged into the plane of the entrance slit of the spectrograph; column image and slit are parallel. A simplified plane view of the optical arrangement is shown in Fig. 1. A concave mirror on the other side of the arc reflects a beam of "probing" radiation back through the source into the spectrograph. The spatial distribution of the absorption coefficient can be derived from the transmission profile of the column. This means that the entire cross section of the arc must be probed. The arc source is mounted on a table which permits precise lateral motion for the scanning. The reflecting mirror is pivoted (vertical axis) and tracks the moving arc so as to always reflect the radiation from the brightest portion of the arc (which serves as the probing radiation) back into the spectrograph. A probing ray of constant high intensity not only yields more accurate results near the arc boundary, but also facilitates the reduction of the data. The tracking motion of the

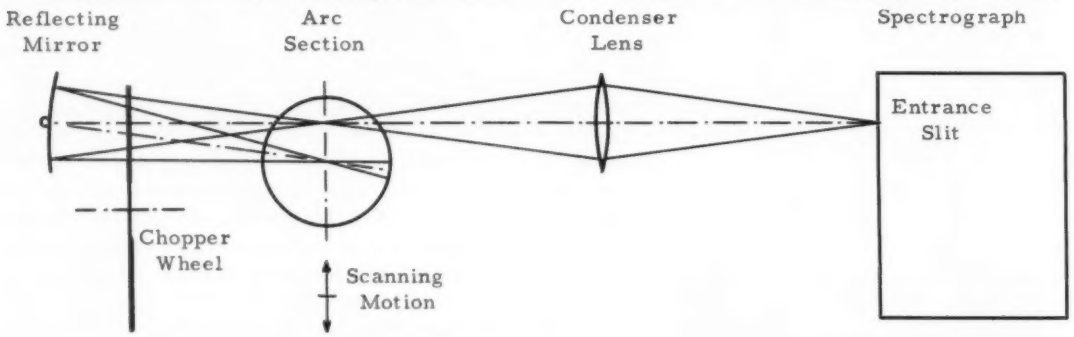
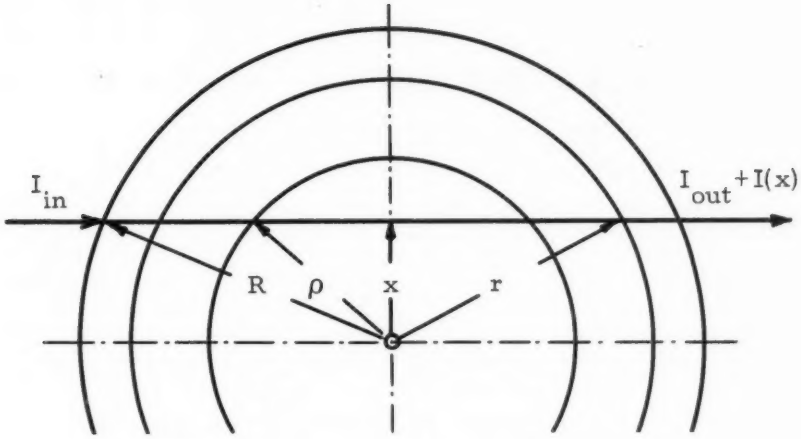


Fig. 1. Optical Arrangement for the Measurement of the Transmission Factor of a Plasma Column.



$$\tau(x) = \frac{I_{out}}{I_{in}} = \exp[-\int a(r)(r^2-x^2)^{-\frac{1}{2}}\, r\,dr]$$

$$I(x) = 2\sqrt{\tau(x)}\int_x^R j(r)(r^2-x^2)^{-\frac{1}{2}}\, r\, \cosh[\int_x^r a(\rho)(\rho^2-x^2)^{-\frac{1}{2}}\, \rho\,d\rho]dr$$

Fig. 2. Transmission Factor $\tau(x)$ and Brightness $I(x)$ of a Self-Absorbing Plasma Column.

mirror is derived from the lateral motion of the table with a simple but precise linkage. When determining the transmission factor of a slab of matter which radiates itself, it is necessary to subtract the emitted energy from the total emerging amount before forming the transmission ratio of the probing intensities alone. A chopper wheel is inserted in the mirror path which provides for the alternate observation of the emitted radiation alone and the superimposed direct and reflected radiation.

The relation between the transmission profile and the local absorption coefficient can be reduced to the well-known Abel integral equation. As the solution involves a logarithmic scale, rather accurate data points are needed. These are obtained with a digital data-acquisition system, which was assembled from commercially available components. The current from the photomultiplier in the spectrograph is transformed into a proportional pulse rate which is counted for periods of one tenth of a second upon command by a sync signal obtained from the chopper. Thus, digital readings of the intensities are formed and subsequently recorded on magnetic tape during the scanning of the arc column. This data-recording system has the noise-suppressing characteristics of a phase sensitive signal amplifier.

The solution to Abel's integral equation is found numerically; it is assumed that the absorption coefficient within narrow ring zones in the source is constant and varies only incrementally from zone to zone. Once the distribution of the absorption in the plasma has been found, the local coefficient of the volume emission coefficient can be computed from the brightness profile of the column. The brightness of a self-absorbing plasma column as a function of the parallax, x, the normal distance of the ray of observation from the axis of the plasma column,

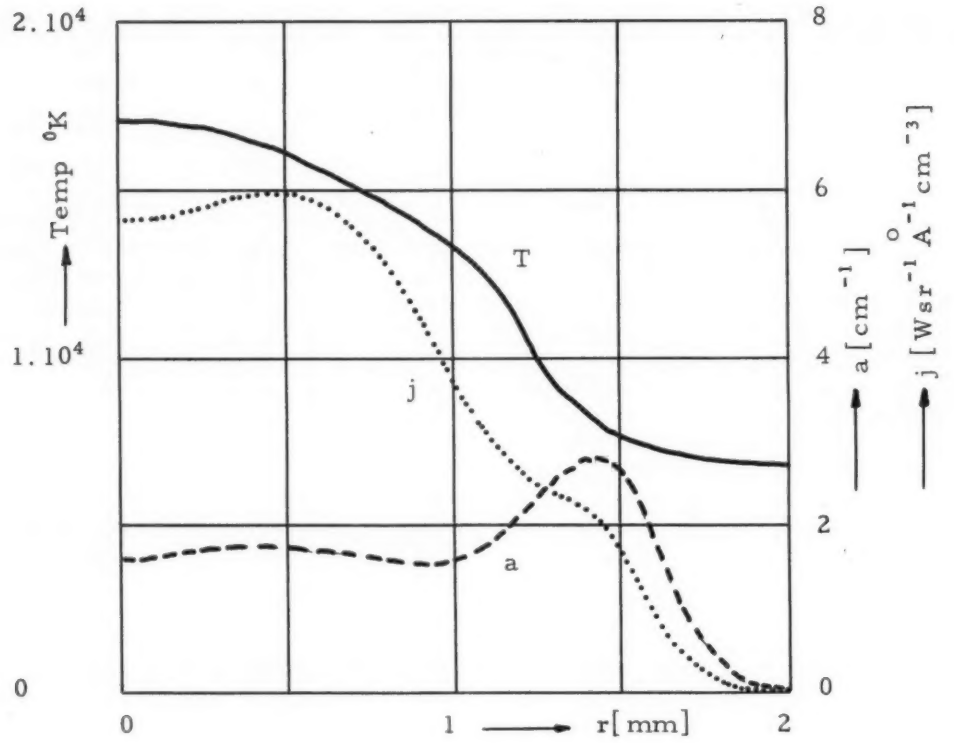


Fig. 3. Distribution of the Coefficients of Emission and Absorption and the Temperature in a Hydrogen Arc.

is

$$I(x) = 2\sqrt{\tau(x)} \int_x^R j(r)\,(r^2-x^2)^{-\frac{1}{2}}\, r \cosh \left[\int_x^r a(\rho)\,(\rho^2-x^2)^{-\frac{1}{2}}\,\rho\,d\rho\right] dr$$

This expression may be verified with the aid of Fig. 2 which also will clarify the notation used. If, again, the intensity values are based on the ring zone picture, the double integral is reduced to a double summation and the emission coefficient in each ring zone can be computed by recursion starting with the outermost ring and progressing towards the center. The method is extremely sensitive to noise associated with experimental data, and either the input or the results must be smoothed. The first alternative was chosen, and parabolas were best fitted to 10 adjacent raw data points; the interpolated center points represented the smoothed profile points which were subjected to the transformation.

Kirchhoff's law can be used to obtain the temperature distribution in the arc cross section if Local Thermal Equilibrium prevails in the plasma. Kirchhoff's law states that the ratio of the coefficients of spectral emission and absorption equals the emission of a black body which follows Planck's radiation law. The method has been applied to a stabilized hydrogen arc at the wave length of the red Balmer line, and yields the temperature distributions shown in Fig. 3. The hydrogen arc was operated at atmospheric pressure with a total current of 150 amps, conditions which permit the assumption of Local Thermal Equilibrium. ★

EARTH-SPACE

MILLIMETER-WAVE COMMUNICATIONS

MICROWAVE PHYSICS LABORATORY, AFCRL

The question is not whether the use of millimeter waves is feasible in earth-space communications. It is one of defining system limitations and parameters. With the increasing demand for band width in the already crowded spectrum of lower frequencies, there is no way of satisfying needs except in the millimeter region. After three years of planning, equipment accrual and tests, Dr. Edward E. Altshuler and his group at AFCRL have recently begun a program to define limitations and parameters for earth-space communications.

The AFCRL program centers around a high-precision paraboloidal antenna designed to operate at 35 gc--or at higher frequencies with reduced efficiency. The reflector consists of 30 precision segments, each individually adjustable to an over-all surface accuracy of about 0.012 inch of a true paraboloid. The antenna is located in Waltham, Mass.

Millimeter-wave communications for earth-space systems offer two prime advantages. One is the unexploited wealth of band width. Large band widths are needed for high-rate data transmissions--such as television photos. The overcrowded spectrum below the millimeter region now places a serious constraint on the ambitions of those instrumenting space vehicles. The second advantage is that high gain and resolution are possible with antennas of moderate size and these, together with compact system components, are important considerations in space-vehicle construction.

Against these advantages there are, of course, disadvantages. Millimeter waves are strongly attenuated by atmospheric gases, by clouds and by rain. Other problems are atmospheric noise, atmospheric refraction and multipath effects resulting in signal fading. All of these disadvantages are enhanced as the space vehicle approaches the horizon because the signal must then pass through a larger segment of the lower atmosphere.

The performance of an earth-space millimeter-communications system is thus seen to be heavily dependent on atmospheric conditions, on the angle of the space vehicle with respect to the observer, and on transmission frequencies. These are the features that Dr. Altshuler and his group will measure in the investigation of the characteristics of earth-space communications paths. Emphasis will be given to two frequencies, 15 and 35 gc.

To make these measurements, one of the system terminals--either the receiver or the transmitter--must be above the atmosphere in space. Until a satellite transmitting millimeter waves is placed in orbit, the AFCRL group will use such natural radio sources as the Sun, Venus, Jupiter and Taurus A. Because these sources emit incoherent radiation, the 29-foot antenna will operate with a radiometer instead of a conventional coherent-signal receiver. But without a millimeter-wave transmitting satellite, it will not be possible to derive true system performance--particularly band-width information. For this, a coherent signal is needed.

This limitation will be mitigated somewhat by using point-to-point transmissions over a 10-mile path between two ground terminals. With this path it will be possible to derive information on the effects of temperature, pressure and relative humidity, and resultant refractive-index gradients. Also, it will be possible to investigate such related effects as signal scintillation and multipath effects. Multipath refers to a situation where 2 or more components of the transmitted wave arrive at the receiver over different paths. When this happens, wave interference results and signal fading occurs. ★

how NOCTILUCENT CLOUDS form

SPACE PHYSICS LABORATORY, AFCRL

Noctilucent clouds, which four years ago presented a host of mysteries, may be pretty well explained. If the theory which Dr. Robert K. Soberman of AFCRL discussed at the Noctilucent Cloud Symposium held last March in the Estonian Soviet Socialist Republic (U.S.S.R.) is correct, some of the residual mystery--namely, the mechanism of their formation--will have been cleared up.

These glowing clouds are seen at unpredictable intervals during the summer in the high northern latitudes--across Alaska, Canada, Scandinavia and the Soviet Union. (Some have recently been sighted in the Southern Hemisphere.) Occurring at altitudes of 80 km.--above 99.9 per cent of the earth's atmosphere--they are by far the highest of all clouds. But why do they occur only at high latitudes, and only during the local summer? What is their composition? In the past, scientists tended to discount the presence of water vapor at the extreme altitudes where the clouds were observed.

The first step toward explaining these clouds was a series of rocket flights conducted from Sweden by Dr. Soberman in 1962.

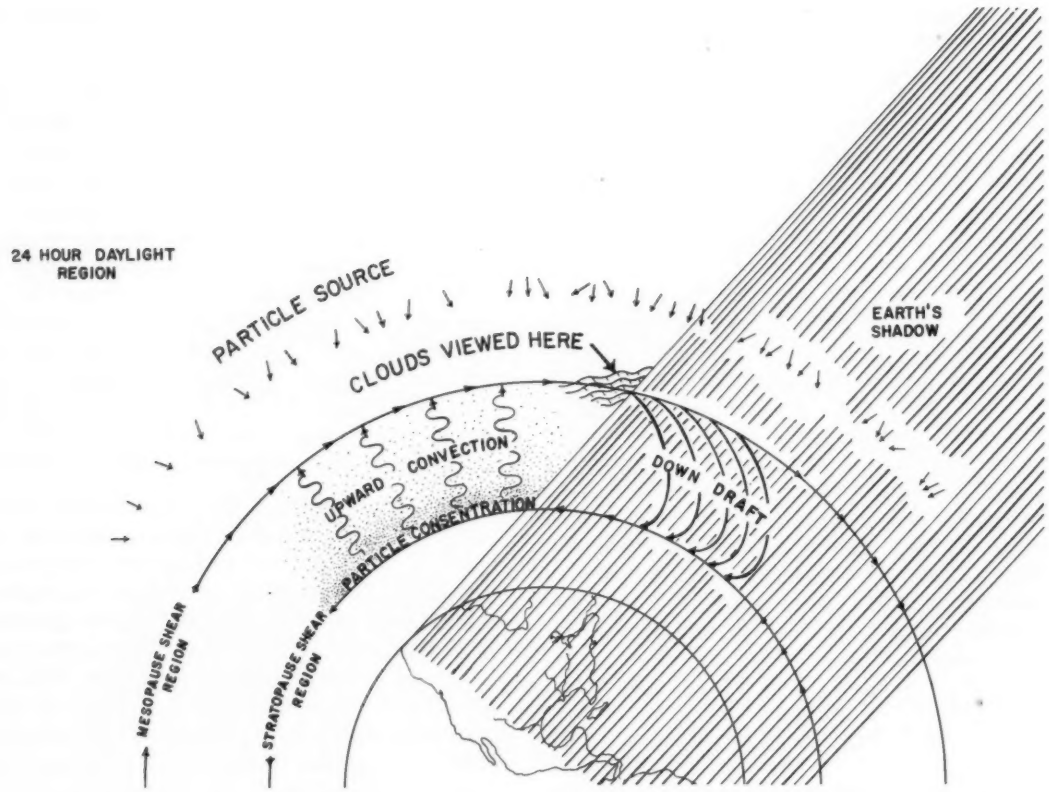


Photo 1. This schematic depicts the mechanism of noctilucent cloud formations as explained by Dr. Soberman's theory.

Photo 2. Noctilucent clouds form at an altitude of about 80 km. and are made visible by sunlight formed below the horizon. This photo was taken during Dr. Soberman's expedition to Sweden in 1962.

These rockets, with extendable collecting surfaces, were flown into the clouds and gathered samples of noctilucent cloud particles for later analysis. Flights during subsequent summers (the last being in 1965 from Ft. Churchill, Canada) established the fact that noctilucent clouds were composed of meteoritic dust particles which, in some cases, were covered with ice.

With this fact established, the chief remaining problems were explaining what processes could produce concentrations of this dust at such extreme altitudes, and why noctilucent clouds form only at high latitudes in summer.

The mechanism proposed by Dr. Soberman provides an explanation of these characteristics and a number of other aspects of noctilucent-cloud behavior as well. Basically, Dr. Soberman's idea is that a small updraft between 50 and 80 km. keeps meteoritic dust from drifting to earth. Over a period of days or weeks a large concentration of the dust accumulates in this altitude region. An updraft lasting long enough for such an accumulation to take place, however, could occur only under certain conditions. These conditions, summer and high latitude, are exactly those under which noctilucent clouds occur.

The reason is that only under these conditions does the atmosphere undergo the continual heating by the sun necessary to sustain an updraft persisting for weeks. It is only at or near the poles during the local summer that months of continuous daylight make this possible.

At lower latitudes, on the dark side of the earth, there would be a corresponding downdraft caused by the falling of the air cooled in the earth's shadow. Thus, a closed system of circulation, much like a storm cell, would exist between 50 and 80 km. The sunlit updrafts of this cell would keep the meteoritic dust from falling, but would not be strong enough to lift this dust "over the top" and into the downdraft in the earth's shadow unless acted on by some outside disturbance. Hence, the dust would collect and concentrate in the updraft until such a disturbance occurred. When this happened the particles would be raised from around 50 km. to about 80 km., the altitude at which noctilucent clouds are seen.

Since this altitude change involves a corresponding temperature drop from a few degrees above zero (centigrade) to -100 degrees C., any water vapor present would freeze on the condensation nuclei provided by

the meteoritic dust particles. They would then be carried along the top of the convection cell from the sunlit side into the earth's shadow. These particles, illuminated by the sun's rays coming from far below the observer's horizon, would be seen from the ground as noctilucent clouds as they pass through the twilight region.

Direct observation of this circulation pattern is unlikely since updrafts of less than half a meter per second are required to keep meteoritic dust particles (which are a few tenths to a few hundredths of a micron across) from falling. However, the mechanism for noctilucent-cloud formation proposed by Dr. Soberman makes testable predictions. One of these, that the clouds should move from southeast to northwest in the Southern Hemisphere because of the effect of the earth's rotation on the circulation pattern, has already been verified. Another way of testing Dr. Soberman's hypothesis would be to track the clouds by means of laser radar during the daytime when they would be otherwise invisible. A number of researchers are presently setting up laser experiments to make this test. ★

PROCEEDINGS OF 1964 AMD SYMPOSIUM AVAILABLE

The proceedings of the Third International Symposium on Bioastronautics and the Exploration of Space, sponsored by the Aerospace Medical Division, AFSC, at the Granada Hotel, San Antonio, Texas, 16-18 November 1964, have been received from the printer and are being distributed. Thirty-three presentations by scientists representing the U.S. Air Force, U.S. Navy, NASA, and various civilian institutions, both national and international, are collected in this publication. Topics range from the life support of the astronauts to astrophysics, astronomy, and primordial organic chemistry. Qualified individuals may obtain copies of these proceedings by submitting their request to DDC (AD 627686). Others may obtain them from the Clearinghouse for Federal Scientific and Technical Information.

ON INVESTIGATIONS OF STATIONARY MAGNETICALLY BALANCED ELECTRIC ARCS IN TRANSVERSE GAS FLOWS

*DR. T. W. MYERS, Thermomechanics Research Laboratory, ARL

The interaction of a gaseous electrical conductor, such as an electric arc, with a gas flow in the presence of a transverse magnetic field is currently of considerable technological interest. The arc-type discharge in crossed convective and magnetic fields is common to a number of magneto-fluid-mechanic devices, e.g., J x B accelerators and arc heaters using magnetically rotated arcs. The configurations which may be used to study this threefold interaction may be basically reduced to two types: those in which the arc is moved along electrodes through a stationary gas by an externally applied transverse magnetic field; and those in which the arc is held stationary with respect to the electrodes by a transverse magnetic field of suitable strength to balance the aerodynamic forces on the arc caused by the gas flow past the arc. (1) It has been found that, in many cases, the motion of an arc along electrodes may be influenced by processes within the anode and cathode regions of the arc. This renders fundamental studies of the interaction between the arc column, the gas flow and the magnetic field very difficult. Therefore, the magnetically balanced stationary-arc configuration, with its stationary electrode roots, appears more attractive and was chosen for experimental investigations of the interaction phenomena.

The balanced-arc configuration shown in Fig. 1 was used with a 20-to-100-ampere arc in a rectangular test section through which argon gas was flowing at approximately atmospheric pressure and velocities up to 300 ft/sec. Magnetic-field strengths up to 30 kilogauss were required to stabilize the arc in the argon stream. This study proved the feasibility of holding an arc stationary in a subsonic transverse argon flow,

** Dr. Myers is a visiting research associate at ARL.*

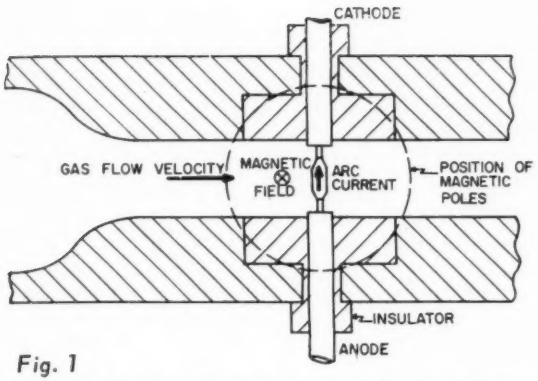


Fig. 1
Sketch of test section showing orientation of arc current, magnetic field, and argon-gas velocity

and showed that the balancing magnetic field, B, was proportional to the square of the gas velocity, V, as shown in Fig. 2. The same relationship would be obtained by equating the aerodynamic force on a cylindrical conductor with the magnetic balancing force at constant current. This balance of forces gives

$$IB = C_d R \rho V^2,$$

where C_d is the coefficient of drag, R is an arc radius, and ρ is the free-stream gas density. By the experiments, no dependence on the arc current, I, was found. Due to limitations of the experimental configuration of the electromagnet and the gas-flow channel, it was only possible to make over-all meas-

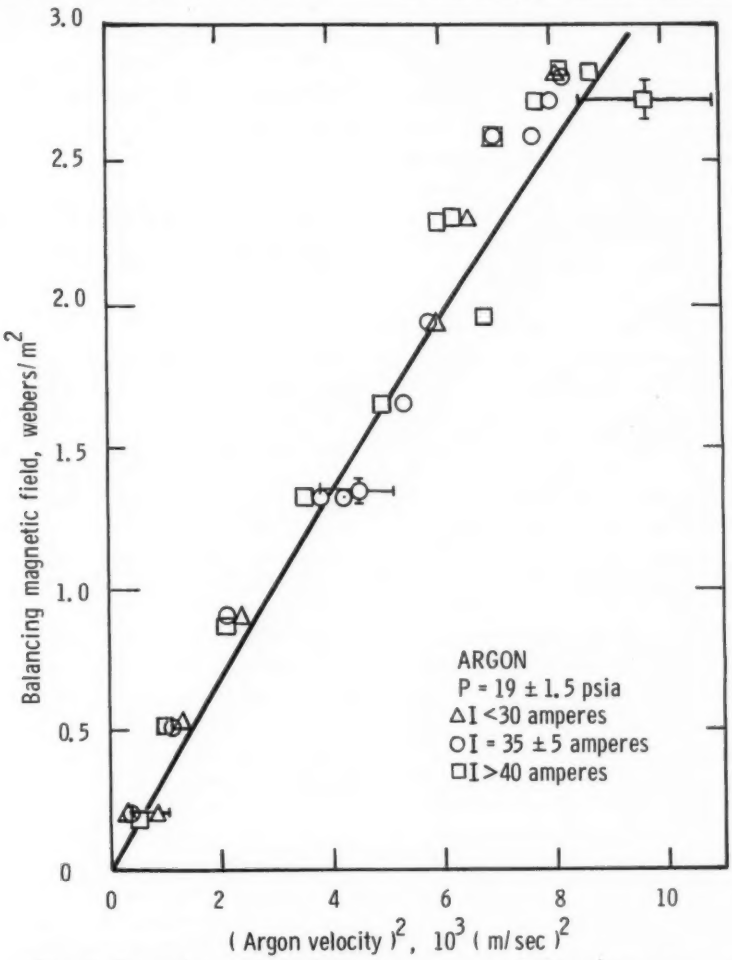


Fig. 2 Dependence of the balancing magnetic field on the square of the argon velocity for a 5/8-inch electrode spacing

urements on the balanced arc; only the arc current and voltage, and the gas properties at stations considerably upstream and downstream of the arc, could be measured. The arc diameter could not be measured and, therefore, the drag coefficient could not be directly determined from the experiments. Thus, the observed independence of the other variables on the arc current could be due to compensating changes in the arc diameter or the drag coefficient.

Measurements of the over-all electrical resistance of the investigated arcs are indicated in Fig. 3 for various levels of current and magnetic-field strength. The values shown are integrated over the arc cross section and the arc length, including the electrode sheaths for which considerable deviations from the integrated values may be expected. If in first approximation the resistance of the discharge in the electrode vicinity may be considered independent of current and magnetic field, the indicated trend reflects the expected decrease of the resistance with increasing current (arc diameter) and temperature and reflects an increase of the resistance due to a frequently observed increase of arc length. Since arc length, arc diameter or temperature distribution throughout the arc column are not known, values of the plasma conductivity cannot be deduced from these experiments.

The follow-up research program at ARL will be concerned with such questions as: How much flow passes around the arc, and how much passes through it? How is the arc-column conductivity affected by the combined presence of the magnetic field and the gas

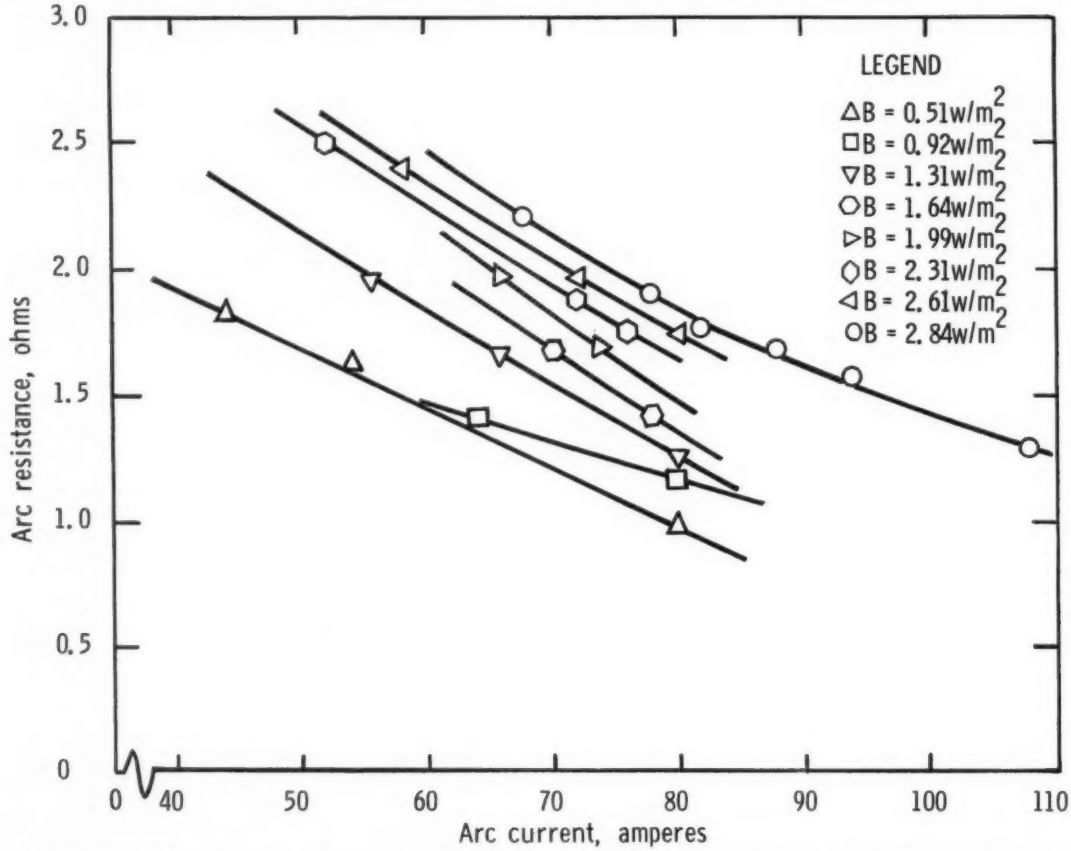


Fig. 3 Dependence of arc resistance on arc current at different constant magnetic fields for a balanced argon arc at a static pressure of 19 psia with a 7/8-inch electrode spacing

flow? How efficient is such a magnetically balanced arc device for adding energy to a gas stream? How does the drag exerted by the arc on the gas stream compare with that of a solid cylinder? How do the arc diameter and current density depend on the flow velocity and magnetic-field strength? What is the effect of the electrode regions on the interaction of the arc with the flow and magnetic fields? How do the electrode effects differ in the balanced-arc configuration from those when the arc moves over the electrode surfaces? The answers to these questions will give a greater degree of fundamental understanding to the present empirical procedure necessary in the design of devices where this threefold interaction is present. ★

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(1) Myers, T. W., C. N. McKinnon and J. C. Lysen, "Experimental Investigation of a Magnetically Balanced Arc in a Transverse Argon Flow," ASME Preprint 65-WA/ENER-1.

PHONONS, MAGNONS AND COUPLED TRANSMISSION LINES

MICROWAVE PHYSICS LAB., AFCRL

A new insight into magnetic-wave propagation in single-crystal materials has been described by James C. Sethares of AFCRL. Sethares' model involves a coupling process between the magnetic and acoustic waves in an energized ferrite crystal. Essentially, the model provides a more convenient mathematical method for calculating the energy density of magnetic waves.

The quantum terms for magnetic and acoustic waves are magnons and phonons, respectively. Only microwave magnons and phonons are of interest in the Sethares study--wave lengths on the order of 1 to 10,000 angstrom units. When magnon and phonon waves are of equal length, energy exchange between them is possible. Because of the small wave lengths involved, a very large number can be accommodated in a single-crystal specimen an inch or so long. The crystal can thus be considered a transmission line. Propagation conditions of magnons and phonons in the crystal are found to be similar to those encountered in coupled transmission-line theory. Coupling exists when power can be transferred from one line to another.

Sethares' model consists of two coupled transmission lines, one for the magnon mode, the other for a phonon mode. This model is believed to be the first of its kind. The unique feature of the model lies in the choice of variables used to describe magnon wave propagation. The variables are chosen in analogy to those for phonon wave propagation. Phonon waves are generally described by force and velocity fields, proportional, respectively, to spatial and temporal derivatives of displacement. The product gives the energy density carried by the phonon.

Magnon waves may also be described by two vector fields, proportional, respectively, to spatial and temporal derivatives of magnetization. The product of the fields gives the energy density carried by the magnon. Voltage and current along the transmission lines are taken to be proportional to the spatial and temporal derivatives of magnetization and displacement. Distributed inductive and capacitive coupling may exist between lines.

One of the benefits of the model is that it permits the microwave physicist to draw from known results of coupled transmission-line theory and to apply these known results to the prediction of new magnetoacoustic phenomena.

The generation, detection, amplification, control, and propagation of magnons and phonons is a relatively new and rapidly evolving field of investigation. The physicist working in this field enjoys the best of the two worlds of science and technology. As a scientist, he finds himself in a relatively uncrowded field with new analytical techniques for exploring the internal forces and energies of matter in the solid state. But if he is at the same time associated with a mission-oriented laboratory (as most scientists in fact are), he sees a ready market for the application of the new knowledge in electronic devices and equipments. The work has high potential for improved delay lines, pulse compressors, and for the generation of coherent radio energy well beyond the 50-gc range. ★

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